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**Final Report on
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**Global Failure Modes in
High Temperature Composite Structures**

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I INTRODUCTION

Composite materials have been considered for many years as the major advance in the construction of energy efficient aerospace structures. Notable advances have been made in understanding the special design considerations that set composites apart from the usual "isotropic" engineering materials such as the metals. As a result, a number of significant engineering designs have been accomplished. However, one shortcoming of the currently favored composites is their relatively unforgiving behavior with respect to failure (brittleness) under seemingly mild impact conditions and large efforts are underway to rectify that situation, much along the lines of introducing thermoplastic matrix materials. Because of their relatively more pronounced (thermo)viscoelastic behavior these materials respond with "toughness" in fracture situations. From the point of view of applications requiring material strength, this property is highly desirable.

This feature impacts several important and distinct engineering problems which have been considered under this grant and cover the

- 1) effect of impact damage on structural (buckling) stability of composite panels, the
- 2) effect of time dependence on the progression of buckling instabilities, and the
- 3) evolution of damage and fracture at generic thickness discontinuities in structures.

The latter topic has serious implications for structural stability problems (buckling failure in reinforced shell structures) as well as failure progression in stringer-reinforced shell structures. This grant has dealt with these issues.

Polymer "toughness" is usually associated with uncrosslinked or thermo-plastic polymers. But, by comparison with their thermoset counterparts they tend to exhibit more pronounced time dependent material behavior; also, that time dependence can occur at lower temperatures which places restriction in the high temperature use of these "newer and tougher" materials that are not quite so serious with the thermoset matrix materials.

From a structural point of view the implications of this material behavior are potentially severe in that structural failure characteristics are no longer readily observed in short term qualification tests so characteristic for aerospace structures built from typical engineering

metals. Instead, one is now confronted with the question of whether a structure which is subjected to long term loading of the monotonic/static or cyclical type will experience failure even if a short term test was "satisfactory". Even in the relatively high rate of deformations associated with impact problems, these materials offer advantages through the larger energy expenditures required to induce failures.

These considerations play thus a role both in structural collapse through time dependent buckling and in the failure/fracture of structural attachments. In the latter category, the important failure problem in post-buckling of stiffened plate and shell type structures comes to mind, especially when the stiffeners are integrally connected with the plate or shell. We have in mind here the connection of composite lay-ups which are joined together with thickness discontinuities such that potentially high stress concentrations are formed. These types of problems are generic in that they deal with the failure initiation from corners and are of the same kind as those associated with "ply-step-down". However, in the structural stability context, that question is not one of immediate failure since separation of a stiffener from a panel or shell in the post buckling deformation may still absorb a lot of energy before total failure occurs.

With the planned development of high speed aircraft an additional and very important complication arises in the form of elevated temperatures that derive from aerodynamic heating. The types of problems that develop in this context are primarily of two types: (i) because of the uncommon sensitivity of the matrix materials to high temperatures (near their glass transitions) these materials will exhibit increased time dependent response with the result that those loads that are tolerable at normal environmental conditions will produce accelerated creep and failure/fracture; (ii) as a result of the differential thermal expansion of composite materials, stress and deformation states become important which "normally" need not be considered.

It is important to emphasize that all the work under this grant has been performed with emphasis on the structural aspects of the problem. There are many researchers who devote their efforts to the details of the failure process at the fiber level, but there is a dearth of efforts that address the structural failure process such as is of more immediate interest in the design process.

II. RESEARCH REVIEW

In this section we review briefly work on the topic of stiffener separation or panel discontinuity and a general description for the work is given. Rather than provide detailed accounts of the various phases of the past work, we choose to append the primary papers that delineate the accomplishments in greater detail. If synopsized versions are desired they may be gleaned from the abstracts or conclusions in these papers

1. Reduced Panel or Plate Stability Under Impact

It has been observed that low velocity impact of objects on graphite epoxy structure can reduce the residual strength of the composite to less than one-half the original strength. Therefore the strength can be reduced below that level which may be required for ultimate load. This problem can be alleviated by:

- (1) designing to lower strain levels (which lessens the weight advantage of the composite);
- (2) preventing the damage to the composite caused by impacting objects;
- (3) isolating the damaged area to prevent catastrophic failure of the complete component

In order to understand the problems associated with item (3) it is evident that the nature of the spreading damage must be understood. The purpose of this work was to investigate the failure process of impact damaged composites under in-plane loading and evaluate models of the propagating damage zone.

Description of Impact Problem: When highly loaded graphite/epoxy structural components fail, the amount of energy released usually leads to considerable disintegration of the test specimen. Therefore, post mortem investigations reveal very little about the nature of the spreading damage zone. In contrast, the failure of metal structures usually results in a small number of pieces and the structure can at least be pieced back together to aid in any failure investigation.

For composite structures it was, therefore, necessary to observe the failure process of impacted composite structure during the actual failure process. The impact time was estimated assuming Hertzian contact to be about 10 μ s. The time for the stress waves generated by the impact to propagate through the thickness of the panel is about 3 μ s. Allowing for a few reflections and spreading of the waves, the time for damage in the form of delamination to occur is therefore on the order of 25 μ s. Since this is the same order as the loading, the detailed picture of the local damage presented a very complicated interaction problem. Fortunately, it was not necessary to become involved in the resolution of these details in order to understand the energetics of the failure process and the spreading of the damage.

Impactor System: The impacting projectile (1/2 inch diameter aluminum ball) was propelled by an air gun. This gun consisted of an air reservoir and a solenoid actuated valve. The projectile was muzzle loaded and held in place by lightly coating it with grease. The velocity of the projectile was measured using a laser light source and a photomultiplier tube. The velocity was controlled by adjusting the pressure in the reservoir.

The results of this research has been collected in the following.

Publications: Reports and papers derived from this phase of the grant are listed below. The papers that have appeared in archival publications are appended to this final report.

1. Chai, H., Babcock, C.D. and Knauss, W.G.
"One Dimensional Modeling of Failure in Laminated Plates by Delamination Buckling, *International Journal of Solids and Structures*, Vol. 17, No. 11, pp. 1069-1083, 1981, [GALCIT SM 80-16].
2. Chai, H., Knauss, W.G. and Babcock, C.D.
"Observation of Damage Growth in Compressively Loaded Laminates", *Experimental Mechanics*, pp. 329-337, September 1983, [GALCIT SM 82-4].
3. Chai, H. and Babcock, C.D.
"Two-Dimensional Modelling of Compressive Failure in Delaminated Laminates", *Journal of Composite Materials*, Vol. 19, pp. 67-98, January 1985.
4. Waas, A.M., Babcock, Jr., C.D. and Knauss, W.G.
"An Experimental Study of Compression Failure of Fibrous Laminated Composites in the Presence of Stress Gradients", *International Journal of Solids and Structures*, (Charles Dwight Babcock, Jr. Memorial Issue), Vol. 26, No. 9/10, pp. 1071-1098, 1990, [GALCIT SM 89-9].
5. Waas, A., Babcock, C.D. and Knauss, W.G.
"A Mechanical Model for Elastic Fiber Microbuckling", *Journal of Applied Mechanics*, Vol. 57, No. 1, pp. 138-149, March 1990, [GALCIT SM 89-18].
6. Waas, A., Babcock, C.D. Knauss, W.G.
"Damage Progression in Compressively Loaded Laminates Containing a Circular Cutout", *AIAA Journal*, Vol. 29, No. 3, pp. 436-443, 1991, [GALCIT SM 89-19].

Reports:

1. "Low Speed Impact Damage on Composite Materials," (W.G. Knauss, C.D. Babcock, and H. Chai) GALCIT SM 78-14, September 1978.
2. "Effect of Stress Concentrations in Composite Structures" (W.G. Knauss and C.D. Babcock), GALCIT SM 83-9.
3. "Interaction of Buckling and Delamination in a Laminated Composite," (W.G. Knauss and C.D. Babcock) GALCIT SM 79-6, May 1979.
4. "Fracture Energy of Graphite-Epoxy Composite Laminates," (H. Chai, C.D. Babcock and W.G. Knauss) Informal Report No. 1, GALCIT SM 79-13, July 1979.
5. "The Incorporation of Bending into the Buckling Delamination Analysis," (H. Chai, C.D. Babcock and W.G. Knauss) Informal Progress Report No. 3, GALCIT SM 79-15.
6. "Interaction of Buckling and Delamination in a Delaminated Beam Under Pure Bending," (H. Chai, C.D. Babcock and W.G. Knauss) Informal Progress Report No. 4, GALCIT SM 79-16.

2. Instability

Under this topic we have been mostly concerned with problems related to the stiffener/panel separation which research concentrated on the time dependent stability of columns as examples of evolutionary instability behavior. Following the analytical and experimental study of column buckling under constant load and temperatures, that topic was expanded analytically to include cyclic loading, simulating structural response of an aircraft to on-ground and in-flight loading. In addition, we have dealt with the simultaneous heating of the column such that in-flight (elevated) loads are accompanied by higher temperatures.

The interesting result of the study that used thermorheologically simple material description for instability evolution was, that analysis and experiment agreed rather well, indicating that the typical kinematics of small deformation analysis is sufficient for these types of problems. In addition it confirmed the concept that thermorheological behavior is a powerful tool to deal with these problems, allowing the engineer to rely on this concept for predicting long range behavior from short range laboratory tests and analyses.

In the follow-up study we then examined the response of structures to cyclically imposed in-plane compression (a square wave load profile) which simulates to some degree the loads which an aircraft component might experience in day-to-day operations. Doing this for situations when time dependent properties are important we have demonstrated that the boundary between unstable imperfection growth and stable behavior follows similar rules as the steady load case.

An additional important study was devoted to the effect of a temperature gradient across the structure (column). In this case very significant effect on buckling instability derives from the bowing of the column due to the temperature variation across the column thickness, which bowing provides a potentially large initial imperfection which then grows with time due to the thermorheology of the polymer content in the structure. In fact, the amplitude of this "initial imperfection" is (first Fourier components)

$$B_1 = \frac{4\alpha a l^2}{\pi^3},$$

where α is the coefficient of thermal expansion along the length of the column (assumed independent of the thickness coordinate); a is the gradient dT/dz and l is the column length. This observation points out that under thermal gradients the use of composites will require careful lay-up considerations in order to minimize the thermal expansion characteristics of the panels or shells. Specifically, it will be necessary to effect this lay-up such that thermal variations counteract the lateral imperfection development through choosing the stacking order appropriately.

Three important design oriented observations have emerged from that study:

- a) The growth of the lateral deflections of a polymer based structure is essentially governed by the average of the maximum and the minimum load during a loading cycle rather than by the maximum load during a cycle.
- b) The addition of in-phase cyclic variation of the temperature (in phase with the load), not only accelerates the evolution of instability, but has the further effect of making load levels unstable that are otherwise stable when constant amplitude loading is paired with constant temperatures.

c) In the presence of thermal gradients there appears to be no simple, general scheme which relates buckling under constant load and constant temperature to this situation. As a consequence one is (apparently) forced to deal with rather wide bounds of stability estimates for preliminary design considerations. Such limits have been proposed in terms of buckling behavior under constant load and constant temperature. For more precise predictions it is to compute the response in detail as necessary.

One difficulty in this context was the fact that because of the time dependent change in the stiffness of the laminate the position of the neutral axis or plane moves with time. Thus, if the load is applied at the mid point of the column or plate thickness then there will be two effects: We discussed earlier the fact that the temperature gradient generates an "initial imperfection" deformation in the form of bowing the column to a small but constant curvature. In addition to this imperfection the motion of the neutral plane will cause off-center loading contributing to a bending moment. We know from general principles that this latter effect, which offsets that due to the former, and the relative balance between the two is dependent on the magnitude of the temperature and its gradient.

Publications: The following publications have appeared in the open literature or under revision for publication. They are appended to this report.

- 1 Minahen, T. and Knauss, W.G.
"A Note on Microbuckling in Unidirectional Fibrous Composites", *Journal of Applied Mechanics*, Vol. 56, pp. 983-985, 1989, [GALCIT SM 88-10].
- 2 Minahen, T.M. and Knauss, W.G.
"Creep Buckling of Viscoelastic Structures", *International Journal of Solids and Structures*, Vol. 30, No. 8, pp. 1075-1092, 1993, [GALCIT SM 92-19].
3. Tsuyuki, R. and Knauss, W.G.
"Buckling of Thermoviscoelastic Structures Under Temporal and Spatial Temperature Variations", submitted to the *International Journal of Solids and Structures*, [GALCIT SM 92-46].

3. Section Discontinuities

Under this topic we considered the generic problem of thickness variations in ply-lay-ups; in the extreme case a single ply thickness may represent the discontinuity, while for typical stringer reinforcement cases of structural interest, several ply thicknesses are involved.

The primary objective in the work on this topic was to establish criteria for safe structural design methods. While the current trend in structural analysis is more and more towards the resolution of problems at the smaller and smaller size scale, there is still, today, the need for understanding structural strength in terms of more average or larger-scale description.

We have examined, in this regard, the effect of combining bending and transverse shear in the vicinity of a step down representing a stringer edge. The result of an exploratory study was that the primary effect on failure derives from the bending moment with some strength reduction at higher shear loading. Moreover, only analog specimens as manufactured were used, i.e., without special attention to the step down geometry as exemplified by fillet dimensions.

In 1989, an Engineer's thesis was completed which dealt with the numerical analysis of the ply step down. This analytical work was a precursor to the subsequent experimental work.

This thesis¹ dealt with a new analysis method for composites: While it is customary to analyze certain plane problems under assumptions of plane strain (the plane is chosen transverse to the mid-plane of a plate), this analysis used what was termed a plane-coupled analysis, which allowed for "out-of-plane" (antiplane) deformations coupled to the "in-plane" deformations. Stresses tended to be consistently lower for this case than for the plane strain situation, as expected.

The numerical work examined the stress singularity at the corner of a right angle (sharp) step down. A considerable number of different lay-up configurations were examined with the aim of examining how the magnitude of the singularity term was affected by the lay-up. One interesting result of these analyses was that the extent of the singularity was extremely small, so that the physical argument for failure initiation from corners because of the stress singularity is unrealistic. This somewhat unexpected result heightened interest in the experimental work.

The result of the ensuing experimental study has also been documented in another Engineer's thesis entitled "An Experimental Investigation of the Failure of a Stepped Composite Plate".² Perhaps a primary result of this investigation stands out: In contrast to (or in consort with) the prediction of the analytical results based on continuum concepts the experimental results showed that failure originated primarily at points away from the corner in the step-down.

The important lesson learned from this analytical/experimental program was that structural failure is not necessarily best predicted by continuum and fracture concepts, but that other criteria evolving at the supra-fiber size scale are more appropriate. This fact holds out hope that structural considerations are more efficient than the typical materials and continuum concepts which have been touted for long in the composites community.

¹Kubr, Thomas J., "Stresses Near a Change of Thickness in a Continuous-Fiber-Composite Plate", Caltech Report SM 90-15, 1990.

²Gortsema, Steven C., "An Experimental Investigation of the Failure of a Stepped Composite Plate", Caltech Report SM 91-10, 1991.

In an effort to perform the experimental studies with rigorously definable deformations and load, considerable planning has gone into designing equipment that allows the independent imposition of multiple loading modes such as tension and bending on suitably configured specimens. The configuration developed for this purpose drew on tensioning the specimens in a hydraulically controlled test frame (MTS) while a linkage mechanism, driven through the torsion mode of the MTS, is used to impose bending moments on the specimen.

This study culminated in two documents that are “firsts” on the topic of structural failure at ply-steps. The net result of that study is that for many lay-ups the interaction between bending and tension is essentially linear, with a negative slope, so that increased tension allows lower moments to be applied. The effect of temperature is basically to change the magnitude of the allowed stress levels without affecting the linearity of the interaction noticeably. The only deviation from this linear behavior occurs when the plies at the interface between the thicker and thinner sections are parallel and are oriented at right angles to the step line. In that case the interaction is provided by a characteristic that is concave with respect to the origin. Initial evaluations indicate that the linear interaction behavior is rather well predicted by a stress criterion (Tsai-Hill), while the other case is best characterized in terms of a modified fracture model.

Publications: The following two papers are in the publishing process. The first of these is being revised at the moment, the second has been accepted for publication. They are appended to this report.

- 1 Lee, S. and Knauss, W.G.
“Failure of Laminated Composites at Thickness Discontinuities Under Complex Loading and Elevated Temperatures”, submitted to *International Journal of Solids and Structures*, 1998, [GALCIT SM 98-1].
- 2 Lee, S. and Knauss, W.G.
“Failure of Laminated Composites at Thickness Discontinuities - an Experimental and Analytical Study”, to appear in the *Applied Composite Materials Journal*, 1998, [GALCIT SM 98-2].

4. Academic achievements

The results of this program have been presented at numerous meetings in the Applied Mechanics community, at meetings devoted to the behavior of composite materials, and meetings of various related professional societies, as well as at university seminars.

This program has produced several advanced degrees. The thesis titles and their authors are listed below:

Chai, Herzl;

Ph.D. thesis: "The Growth of Impact Damage in Compressively Loaded Laminates", March 1982

Waas, A.M.

Ph.D. thesis: "Compression Failure of Fibrous Laminated Composites in the Presence of Stress Gradients: Experiment and Analysis", October 1987

Minahen, T.;

Ph.D. thesis: "Structural Instabilities Involving Time Dependent Materials: Theory and Experiment", May 1992

Kubr, T.;

Aeronautical Engineer's thesis: "Stresses Near a Change of Thickness in a Continuous-Fiber-Composite Plate", June 1990

Gortsema, S.;

Aeronautical Engineer's thesis: "An Experimental Investigation of the Failure of a Stepped Composite Plate", September 1991

Lee, S;

Ph.D. thesis: "Failure of Laminated Composites at Thickness Discontinuities Under Complex Loading and Elevated Temperatures", March 1998